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REMOTE MEASUREMENT OF ICE THICKNESS ON THE SHUTTLE EXTERNAL TANK SURFACE

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INTRODUCTION

One of the outstanding problems in the Space Transportation System (STS) is the possibility of the ice buildup on the External Tank (ET) surface while it is mounted on the launch pad. The tank surface is covered with about 3/4-inch-thick Spray-On-Foam-Insulation (SOFI). The surface of SOFI is quite rough, almost like that of a Florida orange. When the tank is filled with liquid oxygen and liquid hydrogen fuels, there is a very large thermal gradient across the SOFI. If there is a weakness/defect in the foam, cold spots can develop on it, leading to water vapor condensation/freezing. Shuttle launch requirements indicate that ice buildup exceeding 1/8 inch in thickness will result in automatic launch postponement.

Kennedy Space Center (KSC) has the responsibility to make sure that <u>either</u> there is no ice <u>or</u> that its thickness does not exceed 1/8 inch anywhere on the cryogenic tank surface. During the T-2 hours (and holding) period, the Ice Team is allowed to approach the ET surface and monitor/measure frost/ice thickness on it. However, after the resumption of the countdown time, the ET surface can only be monitored remotely from distances ranging from 70 feet to 1200 feet. Thus, there is a need for developing a technique for remote measurement of the thickness of frost/ice on the ET surface during this 2-hour period before launch.

Stennis Space Center-Space Technology Laboratory (SSC-STL) has developed an efficient thermal imaging system for remotely monitoring temperatures on the ET surface. Coupled with a simultaneously-operating TV system, this scheme helps them to locate suspect spots, particularly those covered with frost. However, it cannot locate clear (transparent) ice-covered spots, except by the assumption that spots with temperatures below zero degree centigrade imply possible presence of clear ice on them. In any case, there are no currently available techniques for measuring the thickness of frost, frost-on-ice, or clear ice on the ET surface. Frost by itself is not considered to be a problem. However, frost/ice or clear ice alone, are matters of concern. Due to excessive vibrations during the launch, ice pieces dislodged from the ET surface may strike the Orbiter insulating tiles. It has been estimated that 1/8" x 3" x 3" ice pieces will have enough kinetic energy to cause unacceptable damage to the Orbiter tiles.

A Langley Research Center, Instrument Research Division (LaRC-IRD) team visited KSC on March 28, 1990, at the request of KSC/SSC Ice Team leaders. After extensive discussions, the Shuttle ice buildup problems were summarized as follows:

1. If thermal/TV imaging indicates frost-free sub-zero spots on the ET surface, is there any transparent ice sheet present? How thick is the ice sheet?

2. If frost is visible on the surface, how thick is it? Is there any ice layer under frost? What is the thickness of the underlying ice layer?

The LaRC-IRD team members suggested several active techniques (i.e., techniques requiring injection of external energy into the ET-SOFI surface) for monitoring/measuring frost/ice thickness. They are summarized in Appendix 1. Both the KSC and SSC team leaders stated that current Shuttle launch guidelines rule out all active techniques, and that only passive techniques will be acceptable to the Shuttle Project Office at Johnson Space Center. They further stated that the LaRC-IRD team will have to prove the feasibility of the proposed technique before KSC/SSC will accept it. It is the purpose of this paper to outline a technique for demonstrating the feasibility of a passive technique for remotely measuring the thickness of frost/ice coatings on the ET surface.

PROPOSED TECHNIQUE

The ET surface is uniformly flooded with sunlight (natural or simulated) before launch. Consequently, there is enough EM radiation, in the near and mid-IR spectral ranges, incident on the ET surface at all times. (Even during cloud cover, the solar simulator lamps plus banks of tungsten lamps around the launch pad should provide enough radiation intensity for the proposed technique.) It is proposed to select three neighboring near-IR wavelength bands, one ($\lambda_1 \pm 100$ Å) off-resonance and two ($\lambda_2 \pm 100$ Å and $\lambda_3 \pm 100$ Å) on-resonance, in ice. The ice absorption bands will be selected such that for a solar simulator lamp located at 100′ from the test ET surface, the equivalent preceptable water thickness of Florida air (typical RH = 60%) will not exceed 10% of the critical water mass loading (3mm) on the ET surface. Figure 1 shows a schematic diagram of the measurement scheme. The two spectrophotometers receive radiation scattered from selected areas on the ET surface. Spectrophotometer 1 receives radiation scattered from the selected reference area surface only. The second photometer can be aimed at suspect areas on the ET surface. Each photometer is equipped with appropriate filters to accept radiation in all three bands simultaneously.

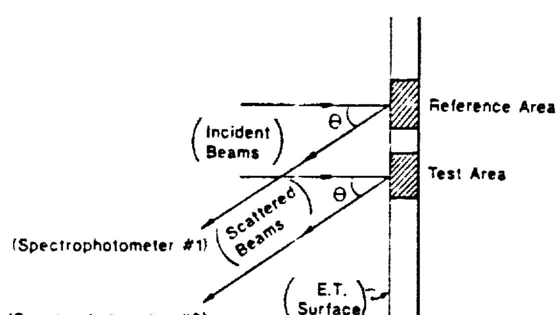

Figure 1

Definitions:

R_{112} = ratio of radiation intensity scattered from the surface of the reference area in bands 1 and 2 into spectrophotometer # 1.

$$= \frac{\Delta I\ (\lambda_1)}{\Delta I\ (\lambda_2)}$$

$$= \frac{\Delta I_1}{\Delta I_2}$$

$$= \frac{I_{inc} \int_{\lambda_1 - 100\ \text{Å}}^{\lambda_1 + 100\ \text{Å}} \int_{\theta 1}^{\theta_2} N_R \frac{d^2 \sigma_R}{d\lambda d\theta}\, d\lambda d\theta}{I_{inc} \int_{\lambda_2 - 100\ \text{Å}}^{\lambda_2 + 100\ \text{Å}} \int_{\theta_1}^{\theta_2} N_R \frac{d^2 \sigma_R}{d\lambda d\theta}\, d\lambda d\theta} \tag{1}$$

R_{113} = ratio of radiation intensities scattered from the surface of the reference area in bands 1 and 3 into spectrophotometer # 1.

$$= \frac{\Delta I_1}{\Delta I_3}$$

$$= \frac{I_{inc} \int_{\lambda_1 - 100\ \text{Å}}^{\lambda_1 + 100\ \text{Å}} \int_{\theta_1}^{\theta_2} N_R \frac{d^2 \sigma_R}{d\lambda d\theta}\, d\lambda d\theta}{I_{inc} \int_{\lambda_3 - 100\ \text{Å}}^{\lambda_3 + 100\ \text{Å}} \int_{\theta_1}^{\theta_2} N_R \frac{d^2 \sigma_R}{d\lambda d\theta}\, d\lambda d\theta} \tag{2}$$

where N_R = No. of scatters/cm^2 on reference surface and $\frac{d^2 \sigma_R}{d\lambda d\theta}$ is the differential scattering cross section from the reference area on the ET surface.

R_{112} and R_{113} are expected to remain constant during the observation period.

Similarly, R_{212} – ratio of radiation intensity in bands 1 and 2 scattered from the <u>test</u> surface into spectrophotometer # 2.

R_{213} – ratio of radiation intensity in bands 1 and 3 scattered from the <u>test</u> surface into spectrophotometer # 2.

Case I - <u>(Pure Frost or Pure Ice on Test Surface)</u>

See figure 2 for an illustration of the problem in 2-D.

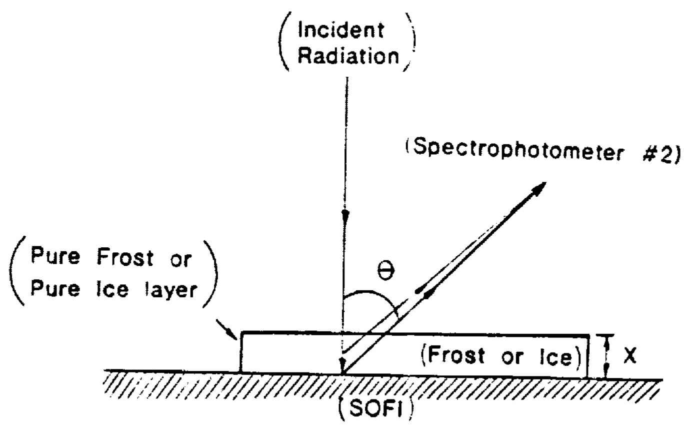

Figure 2

$$R_{212} \simeq \frac{\Delta I_1 \, e^{-K_{1s} x (1+\sec\theta)} + I_{inc} \times \iint N_s \frac{d^2\sigma_S}{d\lambda d\theta} \, d\lambda d\theta}{\Delta I_2 \, e^{-K_{2s} + K_{2a}) \times (1+\sec\theta)} + I_{inc} \times \iint N_S \frac{d^2\sigma_S}{d\lambda d\theta} \, d\lambda d\theta}$$

$$= \frac{\Delta I_1 \, e^{-K_{1s} x (1+\sec\theta)} + \Delta I_1 \, F_1}{\Delta I_2 \, e^{-(K_{2s}+K_{2a}) x (1+\sec\theta)} + \Delta I_2 \, F_2}$$

$$= \frac{\Delta I_1}{\Delta I_2} \left(\frac{e^{-K_{1s} x (1+\sec\theta)} + F_1}{e^{-(K_{2s}+K_{2a}) x (1+\sec\theta)} + F_2} \right)$$

$$= R_{112}\left(\frac{e^{-K_{1s}x(1+\sec\theta)} + F_1}{e^{-(K_{2s}+K_{2a})x(1+\sec\theta)} + F_2}\right) \qquad (3)$$

where

N_S = no. of scatters/cc on frost or ice

$\frac{d^2\sigma_S}{d\lambda d\theta}$ = differential scattering cross section from frost/ice

F_i, besides depending on frost/ice thickness, may also be different for frost and ice.

$$R_{213} \simeq R_{113}\left(\frac{e^{-K_{1s}x(1+\sec\theta)} + F_1}{e^{-(K_{3s}+K_{3a})x(1+\sec\theta)} + F_3}\right) \qquad (4)$$

In equations (1) → (4),

K_{is} = linear scattering coefficient for λ_i for frost/ice

K_{ia} = linear absorption coefficient for λ_i for frost/ice

x = frost (or ice) layer thickness

<u>and</u>

$K_{1s} = K_{2s} = K_{3s} = K_s$ (frost or ice)

$F_1 \simeq F_2 \simeq F_3 = F$ (frost or ice)

Thus a measurement of R_{212} and R_{213}, coupled with the knowledge of K_s, F, K_{2a}, and K_{3a}, should enable a determination of x.

Case II - (Frost + Ice on Test Surface)

See figure 3 for an illustration of the problem in 2-D.

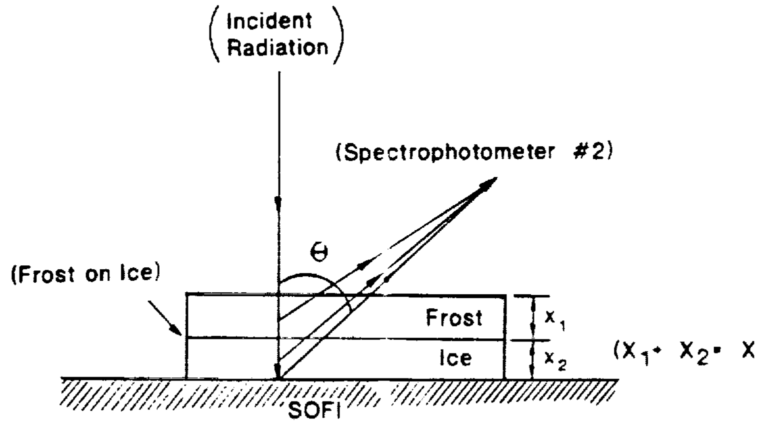

Figure 3

$$R_{212} \simeq \frac{\Delta I_1 \; e^{-K_{1s} \; x_1(1+\sec\theta)-K_{1s}' \; x_2(1+\sec\theta)} + \Delta I_1 \; F_1 + \Delta I_1 \; F_1'}{\Delta I_2 \; e^{-(K_{2s}+K_{2a})x_1(1+\sec\theta)-(K_{2s}'+K_{2a}')x_2(1+\sec\theta)} + \Delta I_2 \; F_2 + \Delta I_2 \; F_2'}$$

$$= \frac{\Delta I_1}{\Delta I_2}\left(\frac{e^{-(K_{1s} \; x_1+K_{1s}' \; x_2)(1+\sec\theta)} + F_1 + F_1'}{e^{-\left[(K_{2s}+K_{2a})x_1+(K_{2s}'+K_{2a}')x_2\right](1+\sec\theta)} + F_2 + F_2'}\right)$$

$$= R_{112}\left(\frac{e^{-(K_{1s} \; x_1+K_{1s}' \; x_2)(1+\sec\theta)} + F_1 + F_1'}{e^{-\left[(K_{2s}+K_{2a})s_1+(K_{2s}'+K_{2a}')x_2\right](1+\sec\theta)} + F_2 + F_2'}\right) \qquad (5)$$

and

$$R_{213} \simeq R_{113}\left(\frac{e^{-(K_{1s} \; x_1+K_{1s}' \; x_2)(1+\sec\theta)} + F_1 + F_1'}{e^{-\left[(K_{3s}+K_{3a})x_1+(K_{3s}'+K_{3a}')x_2\right](1+\sec\theta)} + F_3 + F_3'}\right) \qquad (6)$$

In equations (5) and (6):

K_{is} = linear scattering coefficient for λ_i for frost

K_{is}' = linear scattering coefficient for λ_i for ice

K_{ia} = linear absorption coefficient for λ_i for frost

K_{ia}' = linear absorption coefficient for λ_i for ice

x_1 = thickness of frost layer

x_2 = thickness of ice layer

and

$K_{1s} = K_{2s} = K_{3s} = K_s$ (frost)

$K_{1s}' = K_{2s}' = K_{3s}' = K_s'$ (ice)

$F_1 \simeq F_2 \simeq F_3 = F$ (frost)

$F_1' \simeq F_2' \simeq F_3' = F'$ (ice)

Thus a measurement of R_{212} and R_{213}, coupled with knowledge of F, F', K_s, K_s', K_{2a}, K_{2a}', K_{3a}, and K_{3a}' should permit a determination of x_1 and x_2.

PROPOSED RESEARCH

We have selected the following three near-IR bands for measuring R-values under different conditions:

1. $\lambda_1 = (0.90 \pm 0.01)\ \mu m$ (OFF-resonance)
2. $\lambda_2 = (1.04 \pm 0.01)\ \mu m$ (ON-resonance)
3. $\lambda_3 = (1.25 \pm 0.01)\ \mu m$ (ON-resoance)

These bands have been selected after carefully examining the SSC-STL reflection (scattering) data from frost/ice on SOFI surface in the ($0.4 \rightarrow 2.5\ \mu m$) wavelength range. They may have to be adjusted slightly if our own scattered spectrum measurements require it. We will use a tungsten lamp as the source of test radiation for verifying the selected off/on resonance bands.

The projected research plan is summarized below:

1. Measure R_{112} and R_{113} values for dry SOFI samples to be provided by KSC.

2. Develop techniques to produce frost or ice layers of controllable thickness.

3. Measure R_{212} and R_{213} for various thickness of frost <u>or</u> ice on SOFI surfaces. The frost/ice thickness will range from 1/32" → 6/32". This set of measurements will provide calibration data for measuring pure frost or pure ice thicknesses on an insulating substrate.

4. Test the calibration data developed under 3 above for various combinations of frost and ice thicknesses on an insulating substrate.

After laboratory verification of the proposed technique for measuring frost/ice thickness on the ET surface, the results will be made available to KSC and SSC teams for their use.

SUMMARY

A passive technique is proposed for remote measurement of thickness of the ice layer formed on the external tank surface of the Shuttle during the T-2 hours period before launch. It is based on the comparison of the ratios of the intensities of three preselected near-IR wavelength bands scattered from the "test spot" and a neighboring "reference spot" on the tank surface. The Shuttle is uniformly illuminated by a battery of strategically located solar simulator lamps and banks of incandescent lamps during the prelaunch period. Thus, there should be adequate radiation in the three selected bands incident on the external tank surface during the test period. It is planned to conduct a feasibility study of the proposed technique before recommending it to the KSC/SSC teams for adoption.

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APPENDIX 1

April 2, 1990

Reply to Attn of

TO: 117/Director for Electronics

FROM: 235/Chief Scientist, Instrument Research Division

SUBJECT: Visit to KSC Regarding Shuttle Ice Buildup Problem

An IRD team (Messrs. Jag Singh and Robert Wright) visited Kennedy Space Center on March 28, 1990, to discuss the ice buildup problem on the Shuttle External Tank (ET) Surface while it is mounted on the launch pad. KSC is being assisted by Stennis Space Center-Science and Technology Laboratory (SSC-STL) in measuring ice buildup on the ET surface. We met all members of the KSC Ice and Debris Team and SSC Thermal Imaging Team. They described the nature and extent of the problem in detail, using clear videotapes and color photographs. Shuttle launch requirements dictate that frost/ice buildup exceeding 1/8 inch in thickness will result in automatic launch postponement. At present, the <u>presence</u> of frost, or frost-on ice can be detected by thermal imaging coupled with conventional television. However, there is no technique currently available for detecting clear (transparent) ice. Nor are there any techniques for measuring <u>thickness</u> of frost, or frost-on ice, or clear ice. The problems thus presented to us were as follows:

1. If thermal imaging indicates spots on ET surface colder than 0 ^{o}C, is there a transparent ice sheet present when no frost is visible? How thick is the ice sheet?

2. If frost is visible on ET surface, how thick is it? Is there any ice layer under the frost? What is the thickness of the underlying ice sheet?

3. If frost/ice or clear ice spots are present on the ET surface, what are their thicknesses in units of grams/cm^2? Frost by itself is not considered to be a problem. However, frost/ice or clear ice alone, are matters of concern.

After describing the problem to us, the KSC team leader escorted us to the Launch Pad-39B for a close look at the Discovery and its associated power plants. The surface of the Spray-On-Foam-Insulation (SOFI) on the ET is quite rough. During the T-2 hours (and holding) period, the ice team is allowed to approach the ET surface and monitor/measure frost/ice thickness on it. However, after the resumption of the countdown time, the ET surface can only be monitored remotely from distances ranging from 70' to 1200'. KSC needs help in remotely measuring the thickness of frost/ice during this 2-hour period before launch.

We returned to the SAB conference room and resumed our discussions of the problem and possible solutions. A summary of our proposed solutions follows:

I. Active Technique (Techniques requiring external radiation aimed at the ET)

(i) Direct a CO_2-laser beam tuned-off the broad (10-12 microns) ice absorption band and measure the attenuation of the return signal reflected from the SOFI substrate.

(ii) Direct a CO_2-laser beam (or a tungsten lamp beam) at the "suspect" surface for a preselected time (4 or 5 seconds), switch off the laser/lamp beam, and monitor the temperature of the surface. Both the temperature rise as well as its rate of fall are expected to be functions of the frost/ice mass loading on the ET surface.

(iii) Apply a thin layer (mono-molecular thick) of an appropriate fluorescent dye on the ET surface and monitor the intensity of the fluorescent radiation produced under the incidence of an externally beamed near-IR radiation. The intensity of the fluorescent radiation will depend on the mass of the overlying frost/ice layer.

II. Passive Techniques

(i) Monitor the intensity of radiation reflected from the ET surface in selected near-IR and/or mid-IR bands. The ET surface is flooded with sunlight (natural or simulated) before launch and should provide enough reflected energy in these bands to enable measurement of the thickness of the overlying frost/ice layer.

After further deliberations, both the KSC and SSC teams informed us that only Passive Techniques had a chance of acceptance by the Shuttle Project Office at JSC--at least for the near future. We are now preparing to submit a specific passive proposal for monitoring/measuring frost/ice layer thickness on the ET surface to the Director's Discretionary Fund.

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15. Supplementary Notes

16. Abstract

A passive technique is proposed for remote measurement of thickness of the ice layer formed on the external tank surface of the Shuttle during the T-2 hours period before launch. It is based on the comparison of the ratios of the intensities of three preselected near-IR wavelength bands scattered from the "test spot" and a neighboring "reference spot" on the tank surface. The Shuttle is uniformly illuminated by a battery of strategically located solar simulator lamps and banks of incadescent lamps during prelaunch period. Thus, there should be adequate radiation in the three selected bands incident on the external tank surface during the test period. It is planned to conduct a feasibility study of the proposed technique before recommending it to the KSC/SSC teams for adoption.

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